Transition density of the large mass hyperon star *

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Abstract: The difference between the transition density of a larger mass hyperon star (for example, the neutron star PSR J1614-2230) and that of a smaller mass hyperon star is investigated in the framework of the relativistic mean field theory. We see that the transition density $\rho_{0\mathrm{H}}$ increases with the increase of x_ω (i.e. the mass of the neutron star). For the nucleons parts, the neutrons make the main contribution to the transition density as the baryon density $\rho{=}\rho_{0\mathrm{H}}$. With the increase of the x_ω (i.e. the mass of the neutron star), the relative particle number density of neutrons decreases while that of protons increases. For the parts of hyperons, the Λ and Ξ^- make the main contributions to the transition density as the baryon density $\rho{=}\rho_{0\mathrm{H}}$. The relative particle number density of Λ decreases while that of Ξ^- increases with the increase of the x_ω (i.e. the mass of the neutron star). For the hyperons Σ^-, Σ^0 and Σ^-, the total contributions are less than 16 per cent.

Key words: transition density of a hyperon star, relativistic mean field theory, hyperon star

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1 Introduction

The neutron star is a celestial body with a high density [1]. As the baryon density is small, it only consists of neutrons, protons and electrons. With the increase of the baryon density, the nucleons change into hyperons [2]. At a certain value of the baryon density $\rho_{0\mathrm{H}}$, which is called the transition density of a hyperon star and defined as the lowest baryon density $\rho=\sum\rho_{\mathrm{B}}$ at which $\sum\rho_{\mathrm{H}}{>}\sum\rho_{\mathrm{N}}$ where ρ_{H} is the hyperon density and ρ_{N} is the nucleon density, the neutron star would change into a hyperon star [3, 4].

The neutron star PSR J1614-2230 was observed by Demorest et al. in 2010 [5]. Its mass weighs 1.97 $M_\odot$ and is almost the heaviest one found up to now. It could be assumed to be composed of pure hyperons [6, 7], pure quarks [8, 9] or hyperons and quarks [10], which are in the core of the neutron star.

A non-linear relativistic mean field model, which is consistent with up-to-date semiempirical nuclear and hyper-nuclear data, allowed for neutron stars with hyperon cores and $M>2\ M_\odot$ [11]. According to this method, the mass of the neutron star PSR J1614-2230 can be calculated.

The tensor coupling of vector mesons to octet baryons and the form factors at interaction vertexes would change baryons in dense matter [12]. It was found that the hyperon potentials would influence the mass of the neutron star PSR J1614-2230 [13] and so the hyperonic constituents in large mass neutron stars cannot be simply ruled out [14]. For models that assume the neutron star PSR J1614-2230 only consists of hadrons, the purely nucleonic equation of state is stiff [15]; the range of the hyperon coupling constants corresponding to the mass of the neutron star PSR J1614-2230 was defined by Zhao et al. in 2012 [16].

Although much work has been done on the neutron star PSR J1614-2230, how and when the neutron star changes to a hyperon star is still a mystery. Since the mass of the neutron star PSR J1614-2230 is much larger than those observed before, the properties and the transition densities $\rho_{0\mathrm{H}}$ between them must be different. So knowing how and when the neutron star changes to a hyperon star would help us to understand the difference between the property of the larger mass and the smaller mass neutron star.

In this paper, we examine the difference between the transition density of the larger mass neutron star (for example, the neutron star PSR J1614-2230) and those of the smaller mass neutron star in the framework of the relativistic mean field theory considering the baryon octet.

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2 The relativistic mean field theory and the parameters

The Lagrangian density of hadron matter reads as follows [1]

$$\begin{aligned}\mathcal{L} = &\sum_{\mathrm{B}}\overline{\Psi}_{\mathrm{B}}(\mathrm{i}\gamma_\mu\partial^\mu - m_{\mathrm{B}} + g_{\sigma\mathrm{B}}\sigma - g_{\omega\mathrm{B}}\gamma_\mu\omega^\mu \\ &-\frac{1}{2}g_{\rho\mathrm{B}}\gamma_\mu\tau\cdot\rho^\mu)\Psi_{\mathrm{B}} + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) \\ &-\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\rho_{\mu\nu}\cdot\rho^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu\cdot\rho^\mu \\ &-\frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 + \sum_{\lambda=\mathrm{e},\mu}\overline{\Psi}_\lambda(\mathrm{i}\gamma_\mu\partial^\mu - m_\lambda)\Psi_\lambda. \qquad (1)\end{aligned}$$

The equations of baryons and the mesons can be seen in Ref. [1].

In this work, the nucleon coupling constant is chosen as the GL97 set [1] listed in Table 1.

Table 1. The coupling constants of the nucleons GL97 sets.

	m	m_σ	m_ω	m_ρ	g_σ
GL97	939	500	782	770	7.9835
	g_ω	g_ρ	g_2	g_3	C_3
GL97	8.7	8.5411	20.966	−9.835	0
	ρ_0	B/A	K	a_{sym}	m^*/m
GL97	0.153	16.3	240	32.5	0.78

We define the ratios:

$$x_{\sigma\mathrm{h}} = \frac{g_{\sigma\mathrm{h}}}{g_\sigma} = x_\sigma, \qquad (2)$$

$$x_{\omega\mathrm{h}} = \frac{g_{\omega\mathrm{h}}}{g_\omega} = x_\omega, \qquad (3)$$

$$x_{\rho\mathrm{h}} = \frac{g_{\rho\mathrm{h}}}{g_\rho}, \qquad (4)$$

with h denoting the hyperons Λ, Σ and Ξ.

The $g_{\rho\Lambda}$, $g_{\rho\Sigma}$, $g_{\rho\Xi}$ are given by $SU(6)$ symmetry as follows: $g_{\rho\Lambda}=0$, $g_{\rho\Sigma}=2g_\rho$, $g_{\rho\Xi}=g_\rho$ [17]. So in our calculations, we choose $x_{\rho\Lambda}=0$, $x_{\rho\Sigma}=2$, $x_{\rho\Xi}=1$.

Ref. [18] shows that the ratio of hyperon coupling constant to nucleon coupling constant is in the range of $\sim 1/3$ to 1 [18]. So we can choose x_σ=0.33, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and for each x_σ, the x_ω are respectively chosen as 0.33, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9. Through theoretical calculations, we got the value range of x_σ and x_ω corresponding to the mass of the neutron star PSR J1614-2230 as $0.33<x_\sigma<0.6$ and $0.33<x_\omega<1$ [16]. So, in our calculations, we can respectively choose x_ω=0.3106, 0.4106, 0.5106, 0.6106, 0.7106, 0.8106 and 0.9106, with $x_{\rho\Lambda}=0$, $x_{\rho\Sigma}=2$, $x_{\rho\Xi}=1$ and x_σ=0.5 being fixed, to obtain the small mass neutron star and the large mass neutron star. For the hyperon couplings x_σ and x_ω chosen by us, the corresponding hyperon (Λ, Σ, Ξ) well depths in nuclear matter are listed in Table 2. It can be seen that the hyperon well depths are about in the ranges of ~ -58 MeV to 30 MeV. The experiments show that the value of $U_\Lambda^{(\mathrm{N})}$ is −30 MeV [19], that of $U_\Sigma^{(\mathrm{N})}$ is −27 MeV [20], 90 MeV [21], or 10–40 MeV [22, 23] and that of $U_\Xi^{(\mathrm{N})}$ is −14 MeV [24], −16 MeV [25], or −24 MeV–−21 MeV [26]. The hyperon couplings x_σ and x_ω chosen by us are in part consistent with experiments, namely the larger x_ω values, such as 0.7106, 0.8106 and 0.9106, not being preferred by the well-known attractive Λ nucleon interaction.

Table 2. The hyperon (Λ, Σ, Ξ) well depths in nuclear matter obtained through the hyperon couplings x_σ and x_ω chosen in this work. Here, $x_{\rho\Lambda}=0$, $x_{\rho\Sigma}=2$, $x_{\rho\Xi}=1$ are fixed and the nucleon coupling constant is chosen as the GL97 set.

x_σ	x_ω	$U_\Lambda^{(\mathrm{N})}$/MeV	$U_\Sigma^{(\mathrm{N})}$/MeV	$U_\Xi^{(\mathrm{N})}$/MeV
0.5	0.3106	−58.0943	−58.0943	−58.0943
0.5	0.4106	−43.5432	−43.5432	−43.5432
0.5	0.5106	−28.9921	−28.9921	−28.9921
0.5	0.6106	−14.4410	−14.4410	−14.4410
0.5	0.7106	0.1101	0.1101	0.1101
0.5	0.8106	14.6612	14.6612	14.6612
0.5	0.9106	29.2123	29.2123	29.2123

3 The transition density of the large mass hyperon star and that of the small mass hyperon star

Figure 1 shows the mass of the neutron star as a function of central energy density. We can see that the mass of the neutron star increases with the x_ω increased from 0.3106 to 0.9136 in steps of 0.1. Corresponding to the cases of x_ω=0.3106, 0.4106, 0.5106, 0.6106, 0.7106, 0.8106 and 0.9106, the maximum value of the mass of the neutron star $M_{\max}$ is 1.0187, 1.2490, 1.4869, 1.7016, 1.8666, 1.9700 and 2.013 $M_\odot$, respectively (see Table 3). Here, $M_{\max}$=1.9700 $M_\odot$ stands for the mass of the neutron star PSR J1614-2230. The difference of the mass must lead to the difference of the particle distribution and this further must lead to the difference of the transition density of the hyperon star.

Table 3. The mass of the neutron star calculated in this work. Here, $x_{\rho\Lambda}=0$, $x_{\rho\Sigma}=2$, $x_{\rho\Xi}=1$ and x_σ=0.5.

x_ω	$\varepsilon_c/(\times10^{15}\mathrm{g.cm^{-3}})$	$M_{\max}/M_\odot$	R/km
0.3106	1.0442	1.0187	12.941
0.4106	1.2862	1.2490	12.701
0.5106	1.5824	1.4869	12.354
0.6106	1.8425	1.7016	12.000
0.7106	2.0478	1.8666	11.672
0.8106	2.2457	1.9700	11.330
0.9106	2.4337	2.0130	10.999

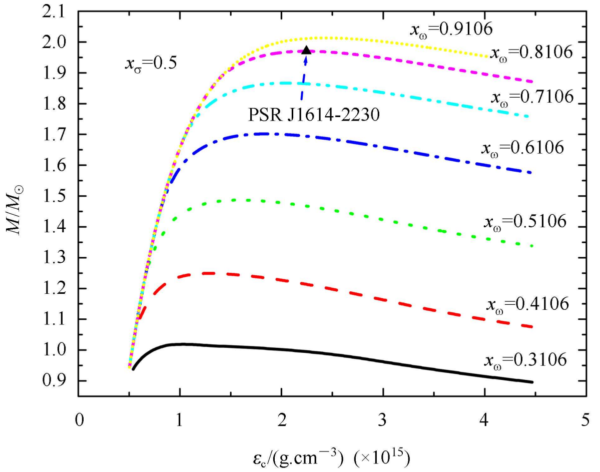

Fig. 1. The mass of the neutron star as a function of central energy density.

The relative particle number density as a function of baryon density is given in Fig. 2. The solid curves represent the nucleons (including neutrons and protons) and the dotted ones represent the hyperons (including hyperons Λ, Σ^-, Σ^0, Σ^+, Ξ^0 and Ξ^-). We see that the density of nucleons decreases while that of the hyperons increases with the increase of baryon density. At a certain baryon density, the relative particle number density of the nucleons would equal that of the hyperons. This baryon density is the transition density of hyperon star $\rho_{0\rm H}$. As the baryon density $\rho>\rho_{0\rm H}$, the relative particle number density of the hyperon is more than that of the nucleon and at this time, the neutron star changes into a hyperon star.

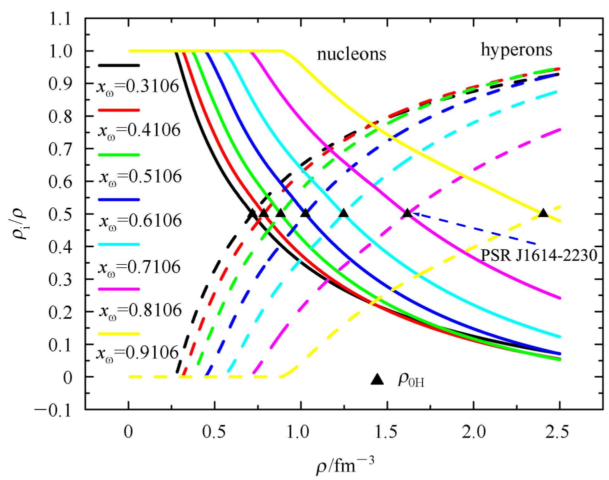

Fig. 2. The relative particle number density as a function of baryon density. The triangles mean the transition density of the hyperon star $\rho_{0\rm H}$.

In Fig. 2, the triangles mean the transition density $\rho_{0\rm H}$ of the hyperon star. We see that the transition density $\rho_{0\rm H}$ increases from 0.719 fm^{-3} to 2.405 fm^{-3} as the x_ω increases from 0.3106 to 0.9106 (see Table 3). From Fig. 1 it can be seen that the mass of the neutron star increases with the increase of the x_ω. This indicates that the larger mass of the neutron star corresponds to the larger transition density $\rho_{0\rm H}$ of a hyperon star. As the $x_\omega=0.5106$, the mass of the neutron star is M=1.4869 $M_\odot$, which is the typical value [1], and its transition density is $\rho_{0\rm H}$=0.882 fm^{-3}. But the transition density of the neutron star PSR J1614-2230 is $\rho_{0\rm H}=1.617$ fm^{-3}. The transition density of the neutron star PSR J1614-2230 is almost two times larger than that of the typical-mass-value neutron star.

The particle composition of the neutron star at the transition density $\rho_{0\rm H}$ of the hyperon star is shown in Fig. 3, Fig. 4 and Table 4. Here, $x_{\rho\Lambda}=0$, $x_{\rho\Sigma}=2$, $x_{\rho\Xi}=1$ and x_σ=0.5. The light magenta lines in Fig. 3 and Fig. 4 represent the transition density $\rho_{0\rm H}$. The lower parts of Fig. 3 and Fig. 4 stand for the contribution of each nucleon and hyperon to the transition density and the numbers 1, 2, 3, 4, 5, 6, 7 and 8 stand for the particles n, p, Λ, Σ^-, Σ^0, Σ^+, Ξ^0 and Ξ^-, respectively.

From the upper parts of Fig. 3 and Fig. 4 we can see that the numbers of neutrons decrease with the appearance of the protons and the hyperons. This means that many of the neutrons change to hyperons. Next, we want to investigate the contributions of the particles to the transition density as $\rho=\rho_{0\rm H}$.

For the parts of the nucleons, the main components are neutrons (see Table 4). With the increase of the x_ω from 0.3106 to 0.9106 (i.e. the mass of the neutron star increases from 1.0187 to 2.0130 $M_\odot$), the relative particle number density of neutrons decreases from 39.94% to 33.15% while that of protons increases from 10.07% to 16.86%. That is to say, the larger the mass of the neutron star, the smaller the number of the neutrons and the larger the number of the protons. The larger mass of the neutron star is advantageous to the change from neutrons to protons.

For the parts of hyperons, the main components are Λ and Ξ^- and the relative particle number density of Λ decreases from 38.27% to 16.82% while that of Ξ^- increases from 6.96% to 18.02% with the increase of the x_ω from 0.3106 to 0.9106, i.e. the mass of the neutron star increases from 1.0187 to 2.0130 $M_\odot$. It can be seen that the larger the mass of the neutron star, the smaller the numbers of the Λ and the larger the numbers of the Ξ^-. The larger mass of the neutron star is advantageous to the appearance of the Ξ^- but is not advantageous to the appearance of the Λ. In addition, the hyperons Σ^-, Σ^0 and Σ^- also make the contributions to the transition density. With the increase of the x_ω from 0.3106 to 0.9106, the total relative particle number density of Σ^-, Σ^0 and Σ^- increases from 4.75% to 15.11%. For the hyperon Ξ^0, there are no contributions.

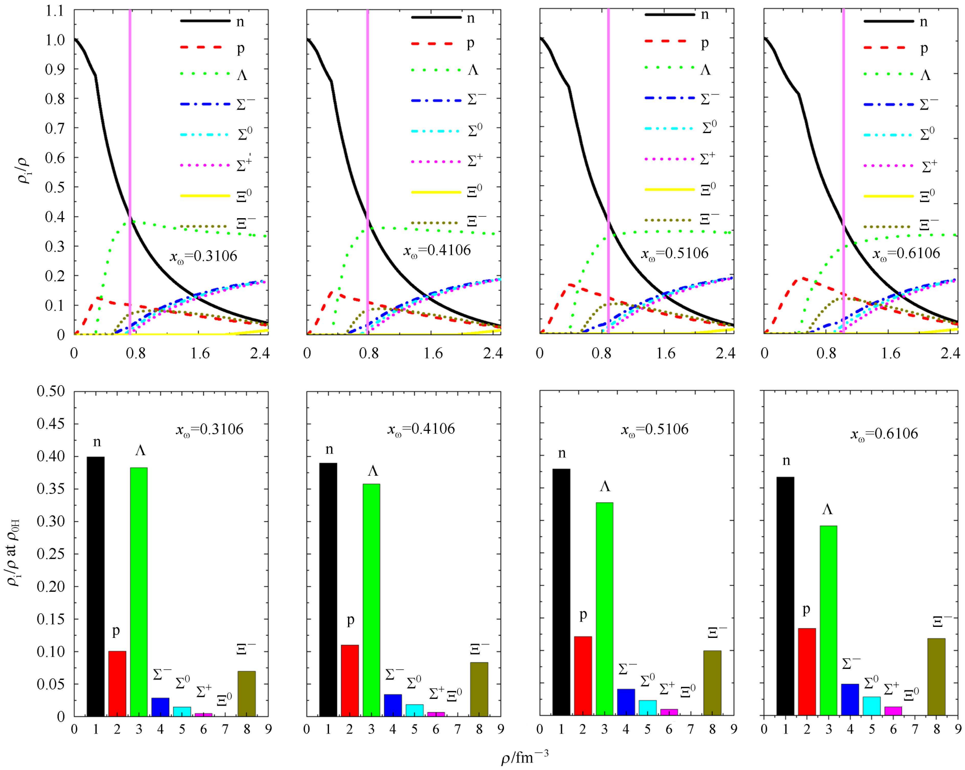

Fig. 3. (color online) The particle composition of the neutron star, respectively corresponds to the cases of x_ω =0.3106, 0.4106, 0.5106, 0.6106, at the transition density of the hyperon star $\rho_{0\mathrm{H}}$. Here, $x_{\rho\Lambda}=0$, $x_{\rho\Sigma}=2$, $x_{\rho\Xi}$=1 and x_σ=0.5.

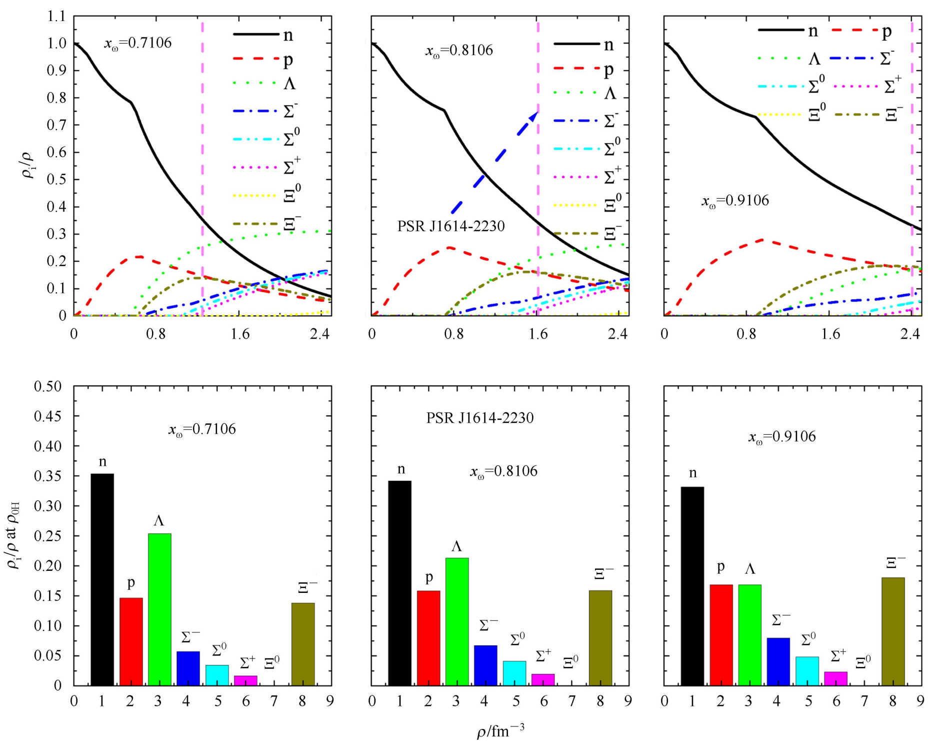

Fig. 4. (color online) The particle composition of the neutron star, respectively corresponds to the cases of x_ω =0.7106, 0.8106, 0.9106, at the transition density of the hyperon star $\rho_{0\mathrm{H}}$. Here, $x_{\rho\Lambda}=0$, $x_{\rho\Sigma}=2$, $x_{\rho\Xi}=1$ and x_σ=0.5.

Table 4. The transition density $\rho_{0\mathrm{H}}$ of hyperon star and the relative particle number density ρ_i/ρ at $\rho_{0\mathrm{H}}$.

x_ω	$\rho_{0\mathrm{H}}/\mathrm{fm}^{-3}$				ρ_i/ρ				
		n	p	Λ	Σ^-	Σ^0	Σ^+	Ξ^0	Ξ^-
0.3106	0.719	0.3994	0.1007	0.3827	0.0283	0.0147	0.0045	0	0.0696
0.4106	0.785	0.3901	0.1009	0.3579	0.0337	0.0185	0.0068	0	0.0831
0.5106	0.882	0.3792	0.1212	0.3272	0.0403	0.0231	0.0095	0	0.0995
0.6106	1.026	0.3667	0.1337	0.2919	0.0482	0.0286	0.0128	0	0.1181
0.7106	1.247	0.3536	0.1464	0.2535	0.0572	0.0347	0.0164	0	0.1382
0.8106	1.617	0.3417	0.1582	0.2128	0.0675	0.0411	0.0198	0	0.1589
0.9106	2.405	0.3315	0.1686	0.1682	0.0799	0.0482	0.0230	0	0.1802

4 Conclusions

In conclusion, the difference between the transition density of the larger mass neutron star (for example, the neutron star PSR J1614-2230) and that of the smaller mass neutron star is examined in the framework of the relativistic mean field theory considering the baryon octet. We see that the transition density $\rho_{0\mathrm{H}}$ increases with the increase of x_ω (i.e. the mass of the neutron star). The neutrons make the main contribution to the transition density for the parts of the nucleons. With the x_ω increased from 0.3106 to 0.9106 (i.e. the mass of the neutron star increased from 1.0187 to 2.0130 $M_\odot$), the relative particle number density of neutrons decreases from 39.94% to 33.15% while that of protons increases from 10.07 % to 16.86%. For the parts of hyperons, the main components are Λ and Ξ^- and the relative particle number density of Λ decreases from 38.27% to 16.82% while that of Ξ^- increases from 6.96% to 18.02% with the x_ω increased from 0.3106 to 0.9106, i.e. the mass of the neutron star increases from 1.0187 to 2.0130 $\mathrm{M}_\odot$. For the hyperons Σ^-, Σ^0 and Σ^-, the total contributions are less than 16 %.

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